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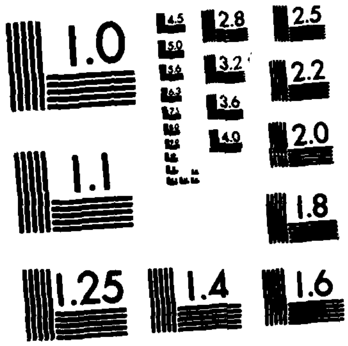
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REPORT NUMBER 4

MEASURING SLEEP BY WRIST ACTIGRAPH

FINAL REPORT

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ABSTRACT

Future warfare may be exceptionally intense and brief, offering personnel little time for sleep. Fatigue could be a crucial factor in combat performance, especially if troops are airlifted across time zones and subjected to jet lag. Therefore, monitoring sleep loss and facilitating adequate sleep are crucial aspects of military medical planning. To monitor sleep in field conditions, a new technology is needed.

People move constantly when awake but little when asleep. Electronic recognition of activity can thus be used to monitor and determine sleep/wake states. This Final Report summarizes the research and development of a wearable sleep monitoring system. Wrist activity is measured with a piezo-ceramic transducer, monitored and stored by a microprocessor, then transferred to a larger computer for automatic sleep scoring. In prospective validation trials, the automatic measurement of sleep by a prototype device correlated r=0.97 with EEG sleep scoring. Full technical specifications are presented for construction of field-deployable sleep monitors which could be worn entirely on the wrist. Deployment of such devices would permit operational objective measurement of sleep loss among our troops.

INTRODUCTION

Sleep loss and combat fatigue are increasing concerns to the modern army. Lapses of attention may be more serious for the soldier who operates smart weapons, vehicles, radar, etc, than they were for the traditional infantryman who carried a pack and dug foxholes. Any future war is likely to be extremely brief and intense, and soldiers using technologically sophisticated weaponry will have little time for sleep. American troops may have to enter combat immediately after being airlifted to remote parts of the world, and plans must be developed to minimize the effects of jet lag on personnel performance.

In order to assess the effects of sleep loss, sleep schedule changes, jet lag, etc, upon operational performance of troops in actual field conditions, a practical method of quantifying sleep is needed which is cost-effective and reliable. Traditional methods of measuring sleep through EEG-EOG-EMG recordings are impractical for actual or simulated combat settings, and subjective monitoring is unreliable (Carskadon et al, 1976). Electrophysiological and observational methods for measuring sleep are also costly, and considerable time is necessary to score EEG records.

In the three years of our contract (DAMD 17-78-C-8040), we have investigated the feasibility of recognizing sleep from measures of wrist activity. We have developed instruments and procedures which allow us to quantify sleep with accuracy comparable to EEG scoring, but with much less expense and inconvenience. In this Final Report, we review and update the research and development reported in prevous Annual Reports and include specifications for building sleep monitors suitable for field deployment. The next step would be to actually build and deploy miniaturized monitors in operational settings. The technical specifications necessary to construct such monitors have been developed, and the monitors could be built today with a suitable engineering investment.

EXPERIMENT 1: SCORING SLEEP FROM WRIST ACTIVITY RECORDINGS

Kupfer et al (1972) and Foster et al (1972a, 1972b) described the use of a telemetric activity recording system for quantifying sleep. Kripke et al (1977) developed a more flexible system for recording wrist activity using a piezo-ceramic activity transducer and Medilog* cassette recorder. Initial pilot results established the value of this analog recording device for quantifying sleep. Kripke et al (1978), using five healthy subjects, obtained a correlation of 0.98 between sleep duration determined from wrist activity and from the EEG. The first experiment to be described here demonstrated the reliability of analog wrist activity recordings for quantifying sleep with a much larger number of recordings and a more diverse group of subjects, including hospital patients with varying degrees and types of insomnia.

Method

The activity transducer was constructed by soldering a small steel nut onto a 5 mm length of spring-like polygraph pen cleaning wire, and clamping the other end of the wire against a piezo-ceramic element (Kripke et al, 1978). The transducer was packaged in a small acrylic box mounted on a watchband. Transducer output was recorded on one channel of a four-channel Medilog cassette recorder. EEG, EOG, and EMG were simultaneously recorded on the other three channels, with timing marks superimposed on the EMG channel. In all, 102 overnight recordings were obtained from 85 subjects, including 39 recordings from 32 hospital patients.

The EEG-EOG-EMG signals (with the time code) were replayed from the cassette to a polygraph at 15 mm/second. Independently, the analog activity recording for the same segment was replayed (with the time code) onto a separate chart at 32 mm/minute. The EEG-EOG-EMG records were scored by one investigator, while activity records were scored independently by a second investigator, blind to the EEG results.

Results and Discussion

Figure 1 shows a representative analog activity recording. Three different sections of the same record (separated by dots) illustrate sleep onset, midsleep, and sleep offset, respectively. Straight lines indicate inactivity while modulations of the line indicate activity. The scorer's sleep/wake determination ('S' or 'W') is noted about the tracings. Periods of sleep and wake can be readily identified by the relative amounts of activity recorded.

The number of minutes for which the activity scorer and the EEG scorer agreed in assigning a score of "wake" or "sleep" was determined for each record. For the entire sample of 102 records, the two scorers agreed on 94.5% of all minutes. Agreement for the 63 non-patient records was 96.3%. The correlation coefficient between the two estimates of Total Sleep Time (TST) was r=0.90,

*Ambulatory Monitoring, Inc., 731 Saw Mill River Rd., Ardsley, N.Y. 10502.

indicating that most of the variance in inter-subject TST scored by one method was represented by the other method. The activity scorer's estimate of TST averaged 15.33 minutes greater per night ($t=3.82$, $p<0.0001$). This trend was related to a tendency to underestimate sleep onset latency in activity records. The activity rater scored sleep onset first in 54 records, while the EEG scorer scored sleep onset first in 34 records. The two scorers agreed exactly on sleep onset in the remaining 14 records. On average, sleep was scored four minutes earlier in activity than EEG records.

Figure 2 compares activity scoring (top line) with EEG scoring (bottom line) for ten records (including seven patient records). Thin lines indicate wake. Disagreement is indicated by a dark area below each pair of lines. Typical were the relatively good agreements between sleep/wake scoring for minutes scored from EEG and from activity recordings, as well as the high correlation between TST estimated by both methods and the small absolute error in TST per night. This confirmed the earlier findings and encouraged further development of a sleep monitor system based on activity recording (Mullaney et al, 1980).

EXPERIMENT 2: TRANSDUCER OPTIMIZATION

Although the piezo-ceramic activity transducer developed by Kripke et al (1977) produced excellent recordings and allowed highly accurate sleep/wake scoring in Experiment 1, the possibility that other available activity transducers might be superior was considered. Experiment 2 compared the piezo-ceramic transducer to a commercially available tilt-switch motion transducer* and to a sensitive accelerometer.**

Method

The tilt-switch transducer and a piezo-ceramic transducer were mounted in a 3.7 x 3.5 x 5.6 cm acrylic box and connected to two channels of a Medilog recorder. A 1.35 V battery and a resistive voltage divider were necessary to match the output of the tilt-switches to the input requirements of the recorder. Four subjects wore the pair of transducers on their wrist for a total of six nights. The two channels were played back simultaneously onto polygraph paper at 32 mm/minute. In further experiments, a second piezo-ceramic transducer in a similar box was firmly taped to the accelerometer. The two devices were connected to two channels of the polygraph and were worn by two subjects for several hours each. The duration of these recordings was limited since the accelerometer had to be directly connected to the polygraph.

Results and Discussion

Figure 3 shows a representative example of the performance of the piezo-ceramic and tilt-switch activity transducers. The piezo-ceramic transducer detected movements repeatedly at times when the tilt-switch transducer did not. Apparently, many movements did not change the orientation of the tilt switch array sufficiently to throw any of the switches. In our entire sample, there were no examples where the tilt-switch transducer detected activity not recorded by the piezo-ceramic transducer.

*Vitalog Corporation, 1058 California Avenue, Palo Alto, CA 94306.
**Grass Instruments, Model SPA 1.

Figure 1. Representative analog activity record visually scored in Experiment 1. Activity is seen as modulations of the line, while straight lines indicate inactivity. The scorer's marks ('S' and 'W') are seen on the record. The first three lines show sleep onset, the middle line mid-sleep, and the last three lines show awakening.

Figure 2. Comparison of the scoring of 10 records from analog activity data (top line) and EEG-EOG-EMG data (bottom line). Thick lines indicate sleep, thin lines wake. Disagreement is indicated by a dark space beneath each pair of lines. Seven of the ten records are from patients.

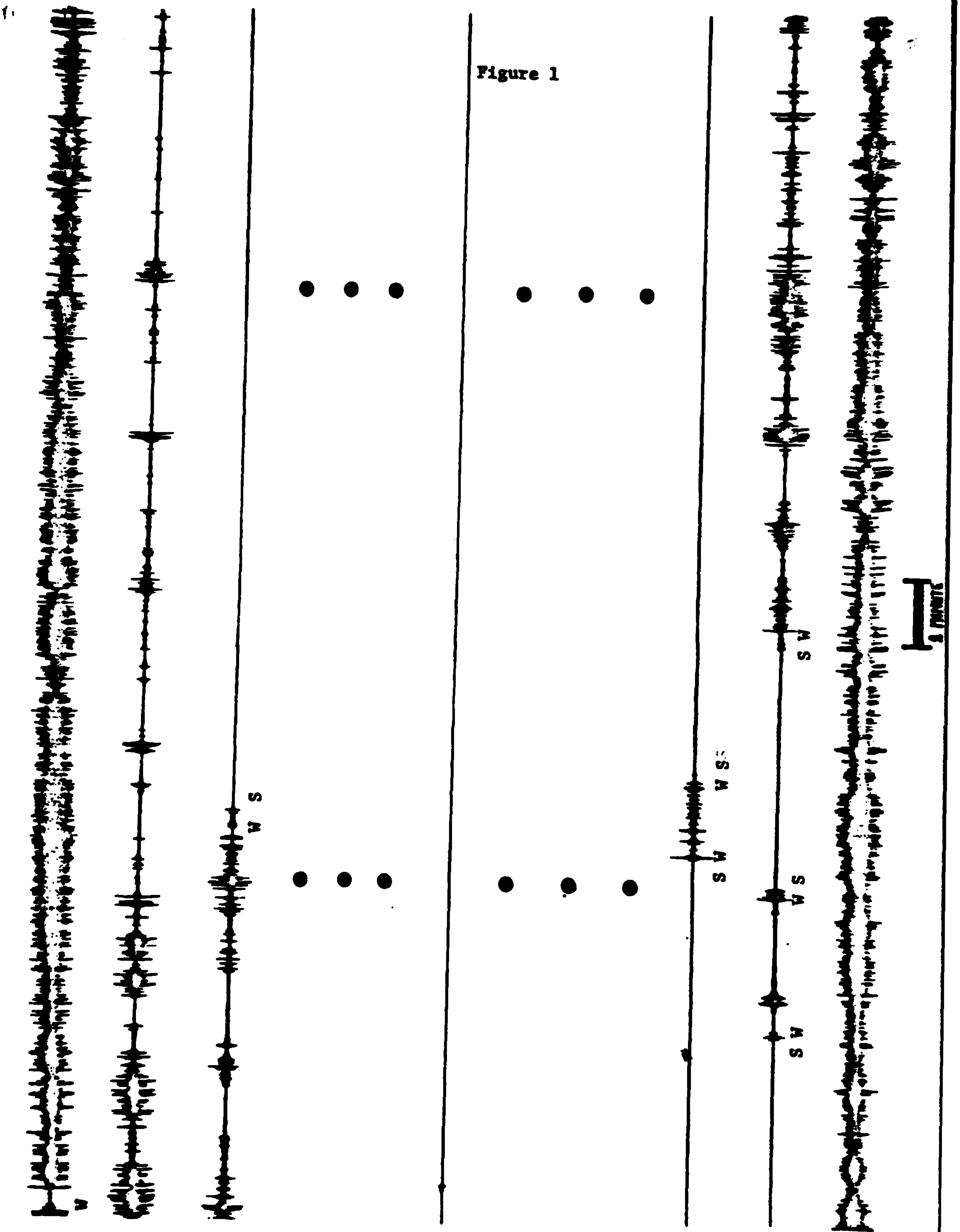
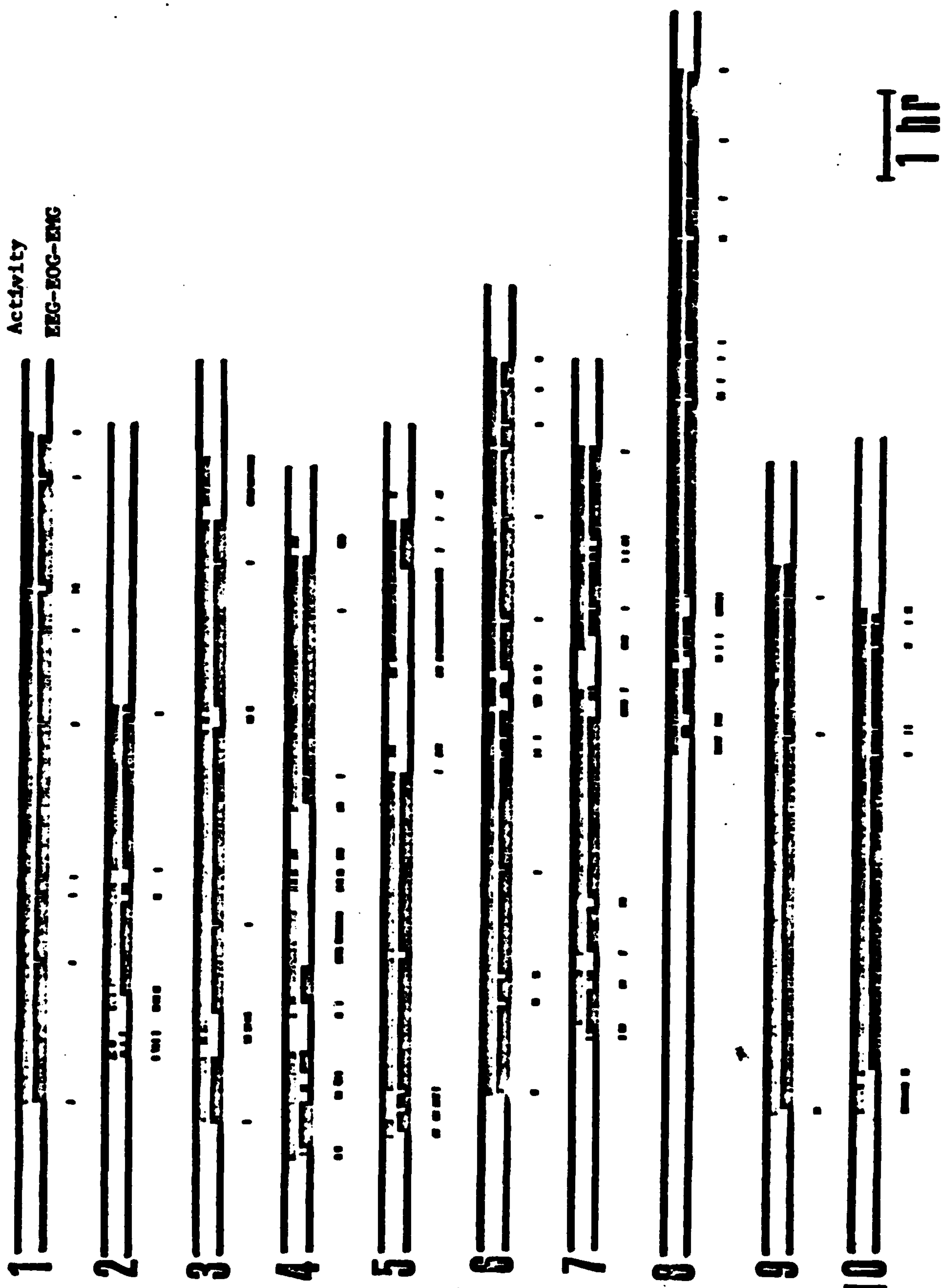


Figure 1

Figure 2



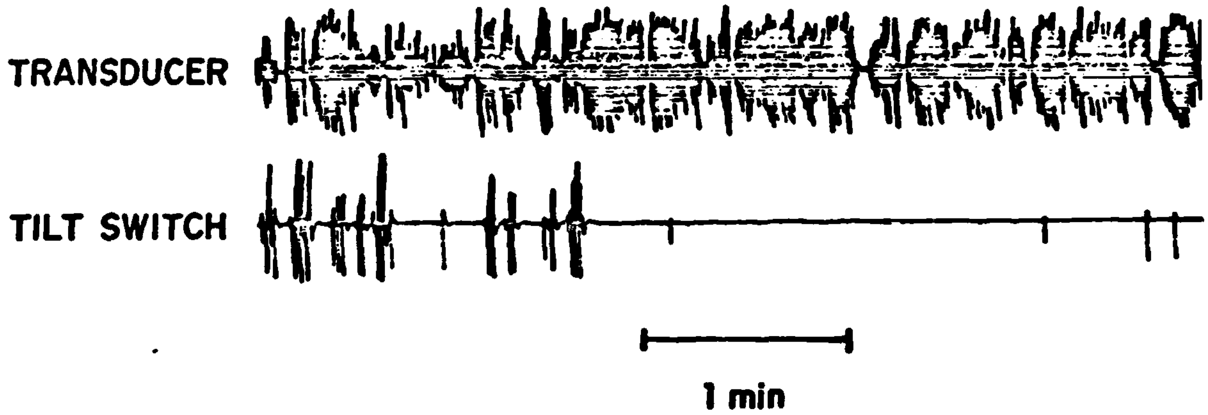


Figure 3. Representative polygraph record of activity recorded simultaneously from piezo-ceramic activity transducer (Channel 1, top) and Vitalog tilt-switch activity transducer (Channel 2). Although the piezo-ceramic transducer measures activity throughout the record, the tilt-switch fails to detect much of this activity.

A representative accelerometer recording is presented in Figure 4. The piezo-ceramic transducer detected all movements detected by the precision accelerometer, but the accelerometer was not sensitive to all movements, presumably due to its uniaxial design.

Thus, the piezo-ceramic transducer compared favorably to alternative designs, yet it is extremely compact, inexpensive and easy to manufacture.

EXPERIMENT 3: TRANSDUCER ORIENTATION

Although the weight is mounted off-center on the spring wire, causing the piezo-ceramic transducer to be excited by accelerations or rotations in any axis, the output voltage was not equalized for each axis. In Experiment 3, transducers were mounted in different axes on the wrist to determine optimal transducer orientation.

Method

Three piezo-ceramic transducers were mounted at three perpendicular orientations within a single 3.7 x 3.5 x 5.6 cm box connected to three channels of a Medilog recorder. Six subjects wore this device on their right wrists for a total of ten nights. The three channels were replayed simultaneously onto polygraph paper at a rate of 32 mm/minute.

Results and Discussion

An example of a recording from the three transducers is presented in Figure 5. This example is representative of the entire sample. Although the recorded activity analog from one transducer was frequently somewhat larger than that from another, there were virtually no instances where movements were not registered by all three transducers, and no clear superiority of orientation could be determined. It was concluded that orientation is not critical for this transducer.

EXPERIMENT 4: TRANSDUCER PLACEMENT

The decision to mount activity transducers on the dominant wrist in previous work was based on the a priori assumption that this location would allow the most sensitive detection of activity. To determine whether mounting on the non-dominant wrist or another area might detect more movements, we simultaneously recorded from both wrists, an ankle, and the forehead. The forehead was chosen with the supposition that all truncal movements would be accompanied by head movement, but respiratory artifacts might be less pronounced on the head than on any site on the body trunk.

Method

Four transducers were mounted in separate boxes (3.5 x 4.4 x 1.7 cm) and connected to the four channels of a Medilog recorder. Nine subjects completed

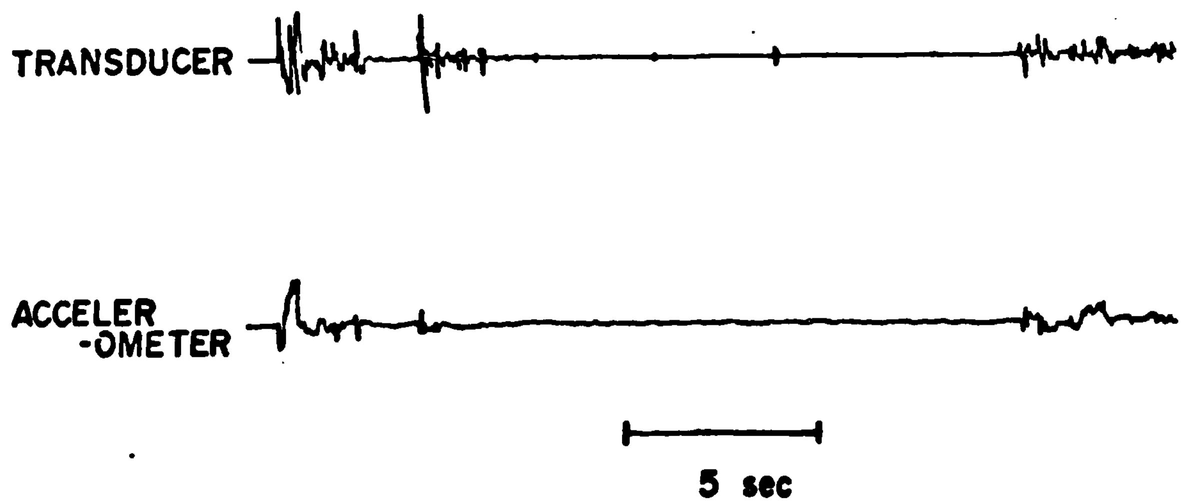


Figure 4. Representative polygraph record of piezo-ceramic transducer (Channel 1, top) and precision accelerometer (Channel 2). Piezo-ceramic transducer detects all activity measured by accelerometer, and some activity missed by accelerometer.

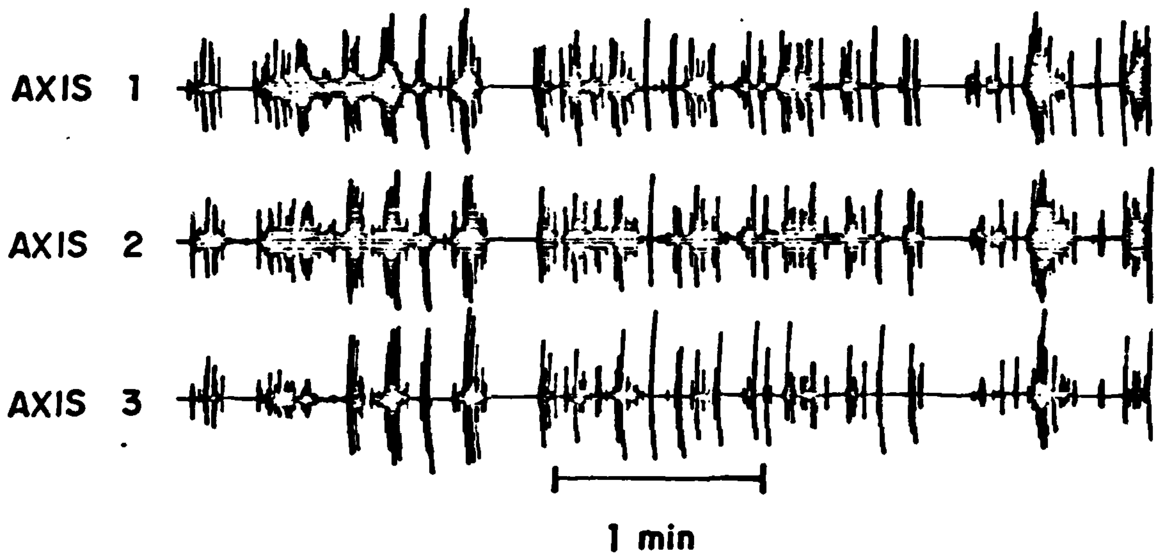


Figure 5. Representative polygraph record of 3 piezo-ceramic transducers mounted at the 3 major axes within a single box and worn on the wrist. Although differences in amplitude occur between the 3 channels, there are no failures to detect activity in any channel.

22 overnight recordings with the transducers worn simultaneously on each wrist, the forehead and an ankle. The assignment of transducers to locations was counterbalanced to control for possible variations in the sensitivity of individual transducers, and the order of polygraphic presentation was also counterbalanced to control for rater bias. The four channels were replayed simultaneously to four channels of the polygraph at 32 mm/minute. The records were then examined by two experienced raters (blind to transducer location) to score each transducer recording for sensitivity to movement and utility for sleep/wake scoring.

Results and Discussion

Figure 6 is part of a typical four-channel recording, showing more movements in the wrists than in either the head or ankle. The raters felt the contrasts between the two wrists were usually very small and of little importance in sleep scoring, and either wrist was preferable to the head or ankle. There was evidence that the left (non-dominant) wrist produced somewhat more activity. The practice of recording wrist activity is supported by these results. The choice of wrists seems unimportant, but the more comfortable non-dominant wrist is probably the better choice.

EXPERIMENT 5: DIGITAL PREPROCESSING

In Experiments 1 to 4, analog activity recordings were collected on cassette tape, replayed to a polygraph, and then scored visually. With this analog system, huge amounts of largely redundant data were collected, much time was expended, both in replaying and scoring recordings, and delicate instruments and trained technicians were required. A much faster and more efficient system would store a measure of activity in a digital memory and make it accessible to a computer for automatic scoring. The first problem in implementing such a system was to find an effective method of expressing a period of continuous activity recording as a single digital value. This experiment compared ten approaches for data compression and digital storage.

Method

Recorded analog activity data were replayed on one channel of a polygraph, and, at the same time, sent through an analog-to-digital converter (ADC) to a Hewlett-Packard 2100 computer. The computer was programmed with ten different data compression algorithms which calculated ten different digital values for each 2-second data epoch. The computer also generated a time code each minute which was written to a second polygraph channel.

The ADC converted the analog signal to a digital value 240 times a second. The 240 Hz conversion rate was chosen to be exactly four times the frequency of 60 Hz electrical noise occasionally recorded (such as that produced by an electric blanket or clock near the bed during the night.) It will be shown that the sum of every four conversions at 240 Hz cancels 60 Hz interference.

A file of seven overnight wrist activity recordings was digitized and transformed into ten alternative digital files corresponding to the ten

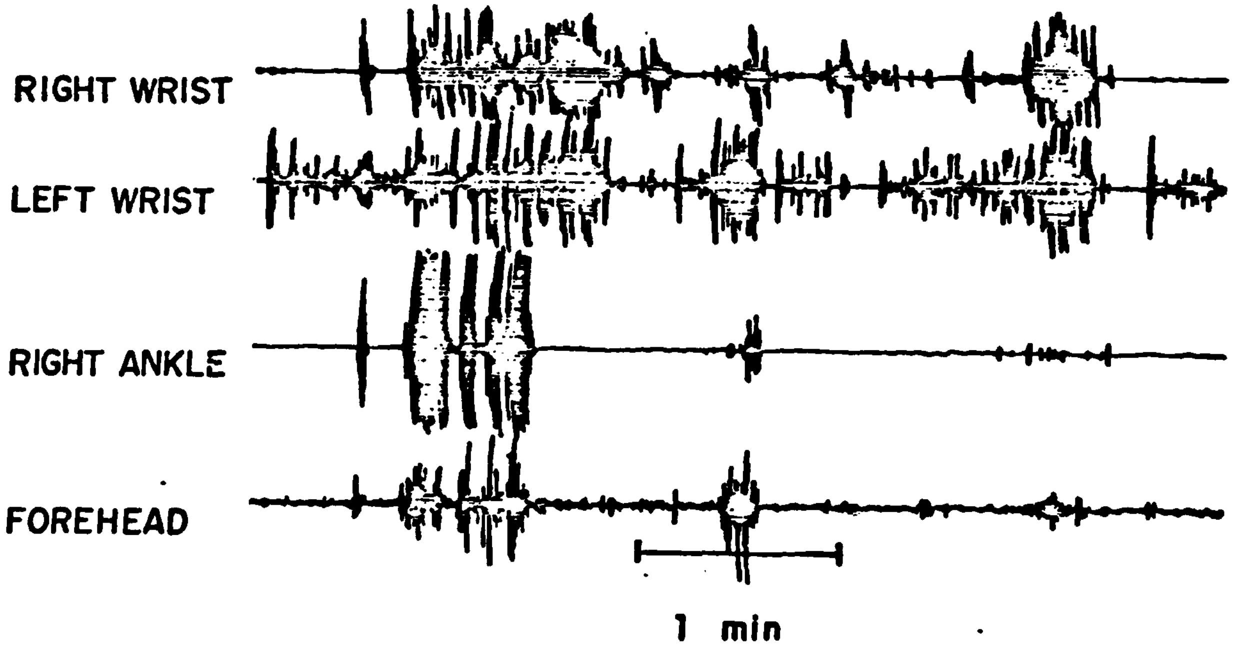


Figure 6. Representative polygraph record of activity detected by piezo-ceramic transducers mounted on the right wrist (Channel 1), left wrist (Channel 2), right ankle (Channel 3), and forehead (Channel 4). Bilateral wrist activity frequently occurs in the absence of head or ankle motion.

algorithms. Portions of the digitized records were displayed on a plotter to compare the ten transformations during different forms of activity. Each of the ten alternative digital files was then scored automatically by the computer using a simple rule in which a minute was scored 'wake' if x of the 30 two-second epoch scores exceeded a threshold of y. Sleep/wake scores for a range of x and y values were compared to the scores assigned by an experienced scorer to the polygraph activity records.

Results and Discussion

Figure 7 shows the plotter display and polygraph write-out of a five-minute portion of a record contaminated with 60 Hz noise from an electric blanket. The ten horizontal traces on the plot represent the ten digital transformations of the analog activity displayed on the polygraph. The vertical lines on the plot separate minutes, which are also marked and labelled with a binary code on the polygraph paper. Of particular interest in this figure is the contrast between traces 1, 3, 5, and 7 and traces 2, 4, 6, and 8 during periods of electric blanket noise. Even-numbered transformations squared conversions prior to summation of each 4 measurements, so all sums were positive and cancellation of 60 Hz noise did not occur. Trnasformations 1, 3, 5, and 7 summed conversions prior to squaring so cancellation of noise can and did occur. The absence of noise in these latter traces indicates the effectiveness of the simple digital filtering technique.

The potential of each of the ten methods of digital preprocessing was evaluated by calculating the maximum agreement between sleep/wake status computed automatically from each digital file and scored from the polygraph activity record. Table 1 presents the rank order of maximum agreement for each record. Despite some variability, the indication from these data is that transformation 5 was superior to the others. (Transformations 1, 2, and 10 were not tested completely since they were judged inadequate after preliminary evaluations). Transformation 5 summed the absolute difference between the activity score for each 1/60th second and the mean of the five preceding and five subsequent scores.

To summarize the preprocessing algorithm found optimal in this experiment, the analog output of the activity transducer was digitized at 240 Hz, and every four digital activity values was summed to produce a value free of any 60 Hz component. Each of the resulting 120 scores (y) in every two-second epoch were then converted to 120 difference scores, $y(diff)=10 * y(i) - [y(i-5) + y(i-4) + y(i-3) + y(i-2) + y(i-1) + y(i+1) + y(i+2) + y((i+3) + y(i+4) + y(i+5)]$, where $y(i)$ is the current 60 Hz sum, $y(i-1)$ the preceding sum, $y(i+1)$ the subsequent sum, etc. The sum of absolute values of these 120 difference scores was the final quantitative expression of activity over a two-second data epoch. Although these algorithms were tested by a retrospective procedure not strictly comparable to prospective scoring, it was encouraging that the median percent agreement obtained for the best algorithm was 91%.

EXPERIMENT 6: SLEEP RECOGNITION

The sleep recognition procedure used in Experiment 5 was an extremely

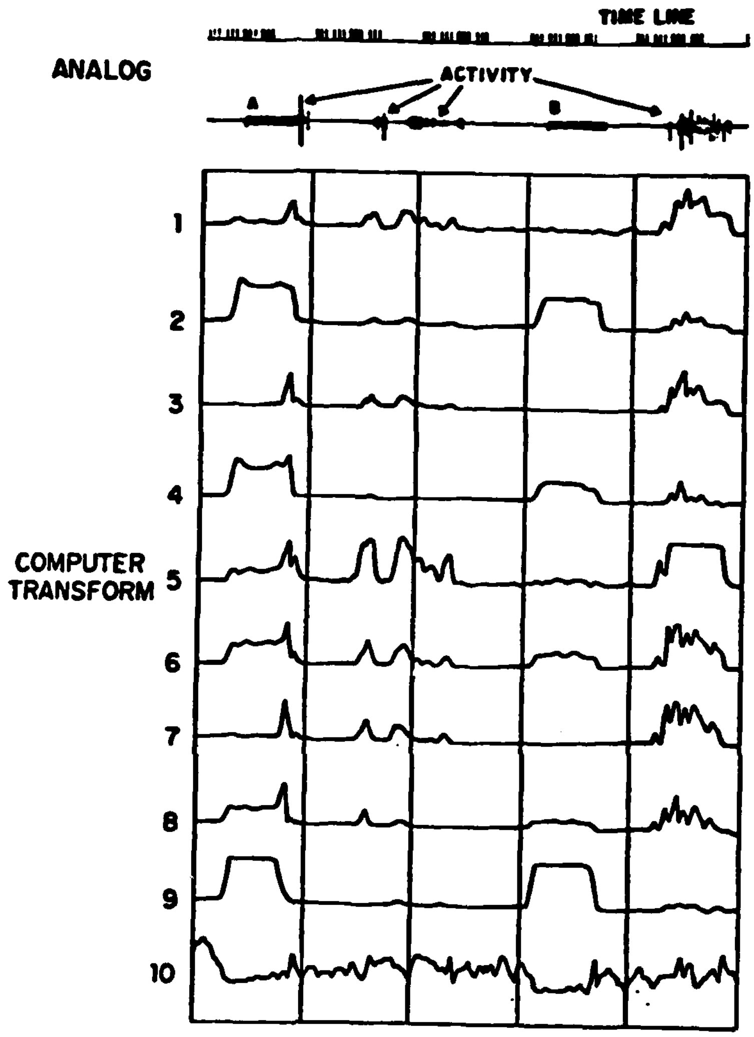


Figure 7. Five-minute portion of analog-polygraph record (top) showing time code and activity mixed with 60 Hz interference from an electric blanket, and plotter display (bottom) showing the ten digital transformations of the same 5-minute segment of activity data. Transformations 1, 3, 5 and 7 effectively filter the 60 Hz noise. A and B are 60 Hz interference.

Table 1.

Rank ordering of agreement scores for 7 of the 10 digital transformations of activity data for each of the 7 records analyzed in Experiment 5.

		Transform Number						
		3	4	5	6	7	8	9
Record Number	1	5	2	6	3	7	1	4
	2	7	2	1	2	2	2	2
	3	6	5	1	3	2	4	7
	4	7	4	1	5	5	3	1
	5	2	2	6	5	6	2	1
	6	2	2	1	2	6	2	7
	7	3	4	1	4	1	4	7
Mean		4.6	2.9	2.4	3.4	6.6	2.6	4.1
Median		5	2	1	3	5	2	4

simple procedure designed to compare preprocessing strategies. Having established an effective preprocessing approach, the next priority was to refine the sleep recognition algorithm for more reliable scoring of sleep.

Method

EEG, EOG, and EMG were recorded from subjects during both wake and sleep, and written onto polygraph paper with a time code. These polygraphic records were then scored for sleep and wake. A wrist activity transducer signal was sampled by the ADC at a conversion rate of 240 Hz. The analog data were preprocessed and stored as described in Experiment 5, but only the optimal transformation (number 5) was used for data analyses. A total of 20 records (13,488 minutes) was analyzed.

Development of the sleep recognition algorithm began with expressions incorporating a weighted sum of combinations of the digital data with potential for discriminating sleep from wake. A minute was scored 'wake' if the weighted sum exceeded a threshold value. For each combination of weights, the agreement between the automatic scoring and EEG scoring was computed, and used as a retrospective measure of the effectiveness of the weighting. The computer varied the weighting of one term at a time iteratively, searching for the combination of weights which produced the highest agreement. Many hundreds of hours of minicomputer time were used to locate the optimal weighting functions.

Seventeen of the 20 records were used in this algorithm development phase. The remaining three records were scored prospectively, ie, each of the three records was scored individually with the single weighting and scale factor found optimal in the development phase. In this prospective test, the laboratory computer simulated the actual deployment of a miniaturized automatic sleep scoring system.

Results and Discussion

One result of the analysis of potential discriminators of sleep and wake was that the most discriminating measure of activity in a minute proved to be the value of the greatest two-second epoch activity amplitude in that minute. For sleep/wake scoring, once the amplitude of the maximal two-second epoch had been entered into the algorithm, no data representing other 2-second epochs from the minute contributed to the discrimination. This unexpected result is extremely fortunate since it allows an entire minute of activity to be summarized by a single value, saving memory space and analysis time.

The optimal sleep recognition algorithm reached after analysis of the 17 records was:

$$D = 0.025 * [.15y(i-4) + .15y(i-3) + .15y(i-2) + .08y(i-1) + .12y(i) + .12y(i+1) + .13y(i+2)]$$

where y represented the value of the maximal two-second epoch score in the current minute, y(i-1) that maximal value for the previous minute, y(i+1) for the subsequent minute, etc. If $D > 1.0$, the minute was scored 'wake', otherwise 'sleep'. The agreement between sleep/wake scored automatically with this algorithm and scored from EEG records was 95.56%. Agreement scores and the proportion of the record scored as sleep by EEG and by the automatic algorithm for each individual record are shown in Table 2.

The ability of this algorithm to score sleep/wake prospectively was tested with the remaining three records. For these records, only the single expression found optimal in the algorithm development phase was chosen prospectively to automatically score sleep/wake. Agreement with EEG scoring and the proportion of the record scored as sleep by EEG and activity are also shown in Table 2. Overall agreement of these three records with EEG scoring was 96.02%.

Since the records analyzed in this experiment varied greatly in length, and included daytime naps as well as overnight sleep, sleep duration was expressed as the proportion of the record scored as sleep (% Sleep). Table 2 includes % Sleep for each record as scored by EEG and as scored automatically from activity data. The automatic scoring method overestimated % Sleep by an average of 1.89% and 2.33% for the retrospective and prospective sets of records. This corresponds to an overestimation of 12.17 and 19.33 minutes per record, or 27.09 and 33.60 minutes per 24-hour day. Correlation coefficients between % Sleep as scored by activity and EEG were $r=0.9889$ retrospectively and $r=0.9982$ prospectively. Automatic activity estimates of sleep percentage thus conformed closely with EEG estimates.

The primary automatic scoring algorithm developed here as well as the visual scoring of analog activity records in Experiment 1 tended to overestimate sleep duration as scored by EEG. This was due in part to the fact that sleep onset is delayed somewhat after all activity ceases. Other phenomena causing overestimation of sleep time from activity were recognized from inspection of error listings. For example, a few minutes of inactivity surrounded by many minutes of activity usually did not indicate sleep, although it was sometimes scored as sleep by the primary scoring algorithm. These considerations led to the development of a final stage of the sleep rcognition algorithm in which corrections of this nature were made.

In this final stage, the sleep/wake score for each minute as determined by the automatic scoring algorithm was subjected to additional corrections. These corrections took the form "after at least x minutes scored wake, the first y minutes scored sleep are rescored wake" and "y or less minutes scored sleep surrounded by at least x minutes scored wake (before and after) are rescored wake." Substituting a range of x and y values into these expressions and rescoring the records scored retrospectively in Experiment 6, a combination of rules emerged which increased still further the similarity between EEG and activity scoring. These rules were: 1) after at least 4 minutes scored wake, the first minute scored sleep by the primary algorithm is rescored wake; 2) after at least 10 minutes scored wake, the first 3 minutes scored sleep by the primary algorithm are re-scored wake; 3) after at least 15 minutes scored wake by the primary algorithm, the first 4 minutes scored sleep are rescored wake; 4) 6 minutes or less scored sleep by the primary algorithm, surrounded by at least 10 minutes before and after scored wake are rescored wake; and 5) 10 minutes or less scored sleep by the primary algorithm, surrounded by at least 20 minutes before and after scored wake, are rescored wake.

This rescoring procedure increased the agreement of the 17 records scored

Table 2.

Record duration, proportion of the record for which EEG and automatically scored activity scores agree, proportion of the record scored as sleep by each technique, and the correlation coefficient (r) between the proportion scored sleep by the two methods. Activity data was digitized by the laboratory computer. Retrospective records (1-17) were those used to derive the scoring parameters, prospective records (18-20) used the parameters derived for the previous records.

Record	Recording Duration (mins)	% Agreement	% Sleep (EEG)	% Sleep (Act.)
1	353	97.17	0.00	2.83
2	574	96.17	45.47	46.86
3	632	95.89	56.80	59.65
4	903	88.82	29.57	34.33
5	660	97.42	54.55	56.21
6	798	95.36	41.73	44.11
7	845	96.80	37.99	40.95
8	1129	96.19	30.65	31.62
9	644	96.89	50.47	51.40
10	553	88.79	56.06	48.10
11	371	96.77	92.72	95.96
12	527	96.96	14.99	16.13
13	226	89.82	93.81	93.36
14	673	91.98	50.67	45.62
15	593	95.78	56.49	59.36
16	829	91.19	40.17	47.77
17	692	94.08	15.17	20.18
Total Retrospective	11002	94.46	42.09	43.98
			r=0.9889	
18	369	93.50	70.19	76.69
19	846	93.62	28.84	31.68
20	1271	98.35	36.82	37.69
Total Prospective	2486	96.02	39.06	41.39
			r=0.9982	

retrospectively from 94.46 to 94.74. The difference in % Sleep was reduced from 1.89 to 0.81, corresponding to 5.24 minutes per record, or 11.65 minutes per 24-hour day. The correlation coefficient decreased negligibly from .9889 to .9868.

A further test conducted with these data sought to determine the resolution in the stored data necessary to achieve these levels of accuracy. The digital activity value was originally stored on disc as a 16-bit value, ie, a number in the range of 0 to 32767. To investigate the bit resolution requirement, the sleep recognition program was repeated with the same data, but the bit resolution was reduced by dividing the data by powers of 2. There was no decrease in agreement with 4-bit data (0-15), and a decrease on only 0.1% was found with 3-bit data (0-7). This surprizing result is important, since it means that data for more minutes can be stored in a given memory capacity. With proper optimization of scaling, 4-bits per minute may be sufficient for reliable sleep/wake scoring. Unfortunately, we have not achieved sufficient experience with the appropriate scale factors to specify which four bits per minute would be most suitable in practice. Certainly 8 bits per minute would be sufficient.

A WEARABLE SLEEP MONITOR SYSTEM

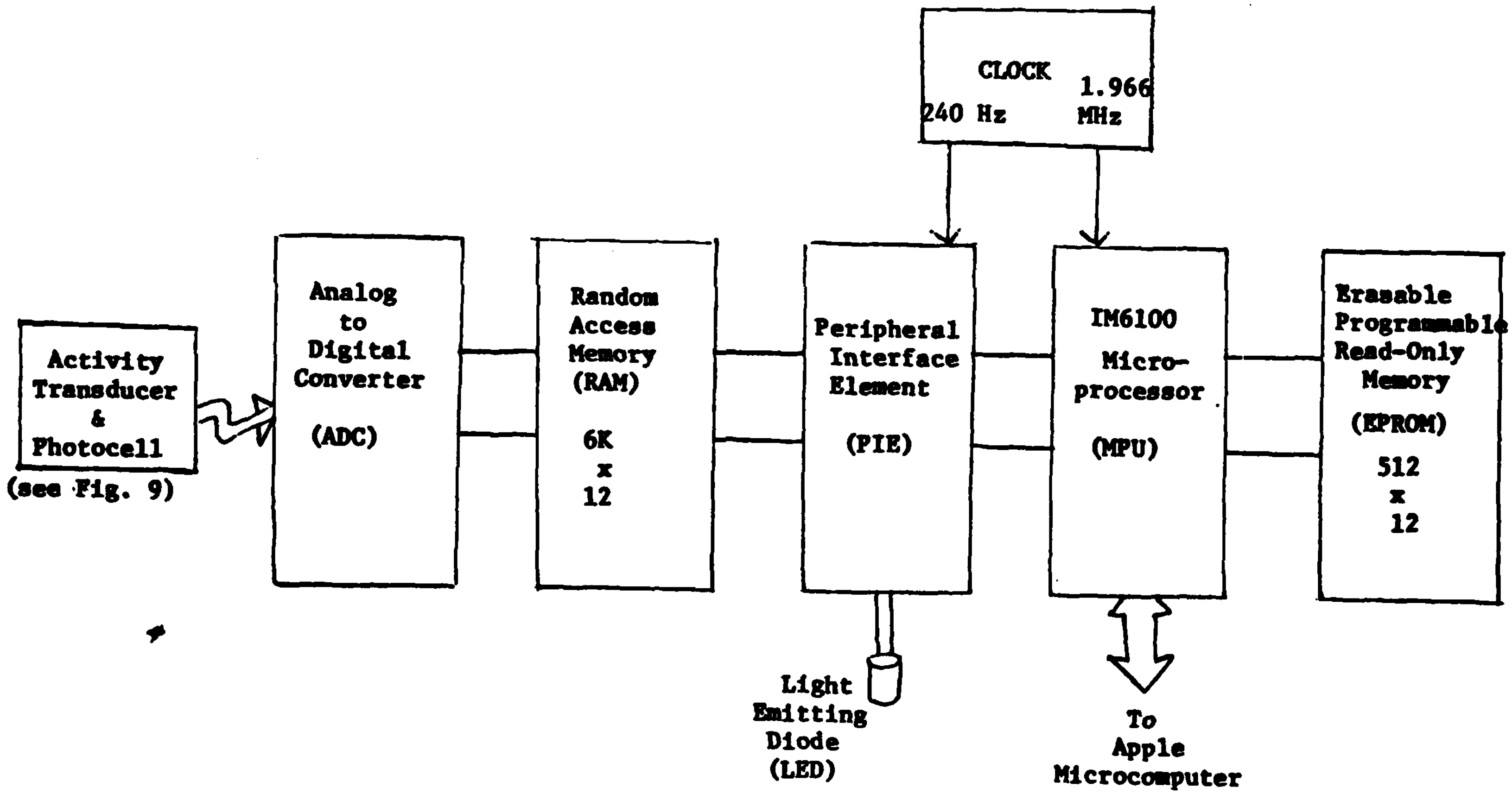
The results summarized to this point were detailed in our previous Annual Reports and have established the feasibility of a sleep monitor system incorporating an activity transducer, digital preprocessor and recorder, and sleep-recognition software. Such a system is capable of quantifying sleep with reasonable accuracy while avoiding the impracticality and expense of polygraphic recording and scoring. Here we describe the implementation of this sleep monitor system in a wearable form.

Digital preprocessing converts the continuous analog signal from the activity transducer to a single digital value for each minute and stores the value in digital memory. To achieve a wearable system, these steps must be accomplished by a digital recorder with the capabilities of a computer, small enough and light enough to be worn comfortably. The monitor must function for days on a battery pack which must also be small and light. To validate these concepts, a wearable monitor was built and tested. Although the prototype was not sufficiently miniaturized for field deployment, it was indeed worn by our test subjects.

To allow validation testing, the Vitalog Corporation* built a package to our specifications incorporating an IM6100 microprocessor, IM6101 programmable interface element (PIE), NSC 809 8-channel analog-to-digital converter (ADC), 6K x 12 random access memory (RAM), crystal clock and a LED indicator light. The entire prototype package, including batteries, is enclosed in a plastic case 15 x 9 x 5-1/2 cm and weighs 480 g. It is about the size of a 35 mm camera and was worn by subjects on a belt around the waist. We built an external activity transducer and connected it to the ADC through a cable. A plug was also provided through which the memory could be acessed by an external Apple II computer. All electronic components were CMOS for minimal power consumption. A block diagram is included (Fig 8).

*Vitalog Corporation, 1058 California Avenue, Palo Alto, CA 94306.

Figure 8. Block diagram of wearable components of sleep monitor system. Activity (and illumination) is detected by the external transducer and transmitted to the ADC. 240 Hz clock pulses generate interrupts which cause the program to activate the ADC, process the digital conversion, and store the results in RAM each minute. An external Apple microcomputer can be connected to the microprocessor to read the data from RAM for permanent storage and sleep scoring. Time information is transmitted through a LED. Communication between the MPU, the ADC and RAM is via data bus and control lines organized by the PIE, which also handles interrupt signals, the wait state, and LED output. Communication with the Apple is handled by an EPROM monitor.



In the following sections, the major components of our prototype and their functions are described in more detail. The actual integrated circuit types and manufacturers are listed only for illustration, as similar systems could be designed with CMOS microprocessors of other manufacture.

IM6100 Microprocessor

Overall control of data collection, processing, and storage was accomplished by the IM6100 microprocessor. The IM6100 is a fully programmable 12-bit microprocessor which is functionally equivalent to a PDP-8/e minicomputer, and it recognizes the PDP-8e instruction set. Internal state timing is generated by a crystal which also produces a 240 Hz interrupt signal. A simple accumulator oriented instruction set proved adequate. An 8-bit microprocessor would have been adequate.

An extremely useful feature of the IM6100 is a wait state, in which program execution is suspended but not halted while power consumption is greatly reduced. Battery drain for the entire package (exclusive of the external transducer which contains its own battery) was measured at 8.5 mA (6V) with the processor running continuously, compared with 3.4 mA when halted. By entering the wait state after processing each ADC conversion, battery drain could be reduced to 5.2 mA. At a drain of 5.2 mA, the battery charge was sufficient to operate the monitor program continuously for 180 hours. By entering the halt mode after shorter recording session, the data could be preserved in the digital memory for even longer periods.

IM6101 Programmable Interface Element

The IM6101 PIE handles all communication between the IM6100, the ADC, and LED indicator light, and an external computer, and controls the wait state. Designed for interfacing peripheral devices to the IM6100, the IM6101 allows efficient interaction with these different classes of I/O without the need for additional external logic, and greatly facilitates interrupt processing. In our realization, the LED indicator was used to signal time codes by which segments of EEG records could be synchronized with the digital scoring results.

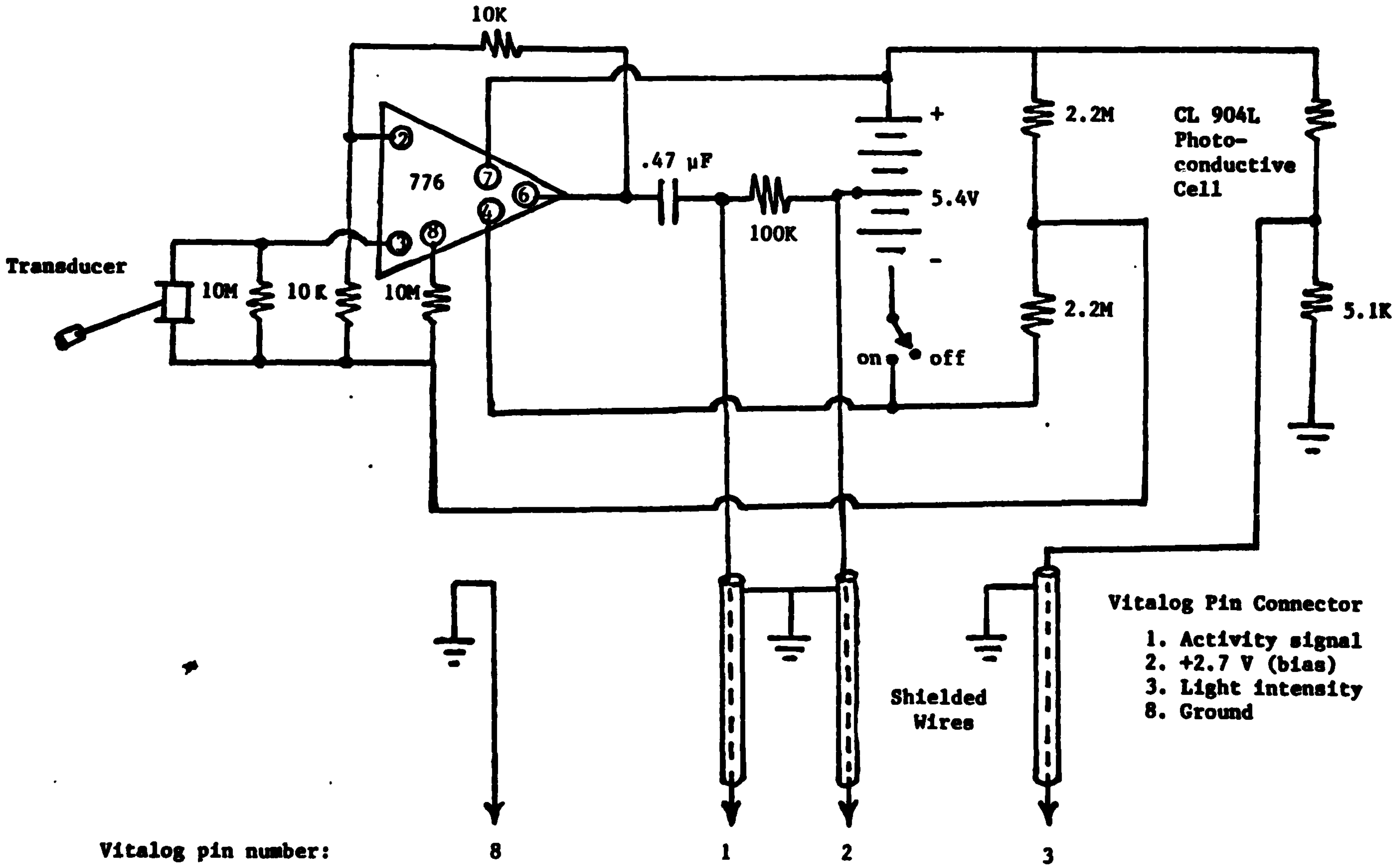
Analog to Digital Converter (ADC)

The ADC converts a voltage in the range of 0 to +5V to an 8-bit digital value (0-255). Up to eight channels of analog data could be sampled by the ADC multiplexer under program control.

External Activity Transducer and Amplifier

As noted above, the ADC converts voltage in the range of 0 to +5V with a resolution of 8 bits. Thus, ground level is converted to "0", and +5V to "255". Maximum resolution is obtained when input voltage covers as much of this range as possible. Since the piezo-ceramic transducer generates only a few milivolts, and alternately produces positive and negative voltage, amplification and level-shifting circuitry powered by a small 5.6V battery was necessary to match the requirements of the ADC. The circuit shown in Figure 9 amplifies the signal from the piezo-ceramic element and shifts it positively so that it alternates

FIGURE 9. SCHEMATIC DIAGRAM OF EXTERNAL ACTIVITY TRANSDUCER, PHOTOCELL AND LEVEL-MATCHING AMPLIFICATION CIRCUITRY



about the level of a center tap in the battery (nominally 2.8V). The signal is amplified so that it covers the full range of 0 to +5V when the transducer is shaken vigorously. This amplified signal is led to the ADC along with the center tap voltage, which serves as a reference. The difference between the signal and reference voltage represents the signed amplitude of the transducer output. A photocell is also mounted in the external transducer package and connected through a resistive bridge to a third channel of the ADC. The voltage level of this photocell circuit serves as a measure of illumination. This can be used as an objective measure of bedtime (defined by "lights out") and can provide some information on the subject's environment.

The Monitor Program

The monitor program (Appendix 1) is loaded from an Apple II microcomputer. After clearing the data memory, the program causes the processor to enter the power-down wait state. On each 240 Hz clock interrupt request, the program determines whether the transducer reference voltage is at ground level, meaning that the switch in the external transducer is off. When the switch is first turned on, increasing the reference level to about 2.8V, the monitor program enters the main data collection, preprocessing and recording routines. In this state, each 240 Hz interrupt request causes the program to read the signal and reference value of the transducer from the ADC, compute the difference (ie, the signed amplitude of the signal relative to its resting level), and sum this value. After each four interrupts, the sum of the preceding four conversions is entered into a differencing function. The sum of every four conversions at 240 Hz represents the 60 Hz digital filter developed in Experiment 5. The differencing function is equivalent to algorithm 5 described in Experiment 5. Specifically, the input to the differencing function is multiplied by 10, and the sum of the preceding and following 5 inputs are subtracted from this product. Then the absolute values of 120 such transformations are summed to form a 2-second epoch score. The largest epoch score for each minute is stored sequentially in memory.

Also, each minute, a voltage indicating the illumination level from the photocell is digitized and stored, and a time code is signaled through the LED. The time code permits external monitoring of the system operation and coordination with polygraphic recording. The monitor program fills 448 12-bit memory locations, leaving 5696 locations available for data storage. This allows us to store two 12-bit data values (activity and illumination) each minute for 47 hours and 28 minutes. Since 4-bit resolution might be adequate, up to 6 times this duration or about 12 days data might theoretically be stored, were the illumination data sacrificed and were battery changes feasible.

SLEEP RECOGNITION SOFTWARE

Having measured, processed, and recorded activity data, the remaining task for a sleep monitor system is to interpret the activity information as sleep or wake. In our prototype system, the contents of the recorder memory were sent to an Apple II microcomputer, which stored the data on discs. The data were then transferred to a more powerful Hewlett-Packard 1000 system for automatic sleep scoring. Automatic scoring used the sleep recognition algorithm which was developed in Experiment 6.

Fourteen digital activity records totalling 12,739 minutes were collected from healthy male college students participating in experiments in which EEG, EOG, and EMG were being recorded. Time codes from the monitor via the LED were written on the polygraph record each minute. Since the physical parameters of the transducer-amplifier-ADC differed somewhat from those used previously, the parameters of the sleep recognition algorithm were recalibrated using the method described in Experiment 6, the computer deriving the optimal sleep recognition algorithm. For these recordings, the parameters producing the best agreement with EEG scoring were:

$$D = .036 \times [.07y((i-5) + .08y(i-4) + .10y(i-3) + .11y(i-2) + .12y(i-1) + .14y(i) + .09y(i+1) + .09y(i+2) + .09y(i+3) + .10y(i+4)]$$

where $y(i)$ represents the greatest 2-second epoch score in minute i, etc, and $D>1.0$ is scored wake. The results of this primary scoring algorithm were then subjected to the rescoring algorithm described in Experiment 6, in which corrections for sleep onset latency and brief periods of inactivity were made. Results are summarized in Table 3. Overall minute-by-minute agreement was 93.88%. The activity estimate of % Sleep exceeded the EEG estimate by an average of 1.03%, corresponding to 9.35 minutes per record, or 14.81 minutes per 24-hour day. The correlation coefficient between the two estimates of % Sleep was r=0.9724.

An additional 14 records totalling 22,514 minutes were scored prospectively using the parameters found optimal in the calibration phase. Twelve subjects were healthy male college students, while two (subjects 12 and 13) were patients with sleep complaints undergoing clinical sleep evaluations. The patient records were included to test the system on highly disturbed sleep records. As seen in Table 4, overall agreement with EEG scoring was 93.04%. The activity estimate of % Sleep exceeded the EEG estimate by an average of 1.20%, corresponding to 19.29 minutes per record or 17.27 minutes per 24-hour day. The correlation coefficient was r=0.9692.

Figure 10 illustrates the scoring of one of the activity records in the prospective series (record 6). The 48-hour record is divided into four 12-hour segments in this figure, and hours are marked along the bottom of each segment. The top trace in each segment plots the maximal activity value for each minute. Below this is the result of EEG scoring of the record (solid indicates wake, light indicates sleep), and below this is the result of automatic scoring of the activity data. The lowest trace in each segment illustrates the agreement between EEG and activity scoring (solid indicates agreement).

ASSESSMENT OF VALIDATION

The results of our prospective validation of the automatic scoring system are comparable to those obtained when the parameters were optimized retrospectively. These results indicate the performance we would expect in an operational application. The wearable sleep monitor system measures sleep with approximately the same precision as the experimental laboratory system developed in Experiments 5 and 6, and visual scoring of analog activity records in

Table 3.

Record durations, proportion of the record for which EEG and automatically scored activity scores agree, proportion of the record scored as sleep by each technique, and correlation coefficient between the proportion scored sleep by the two methods. Activity data was collected with the wearable monitor. Scoring parameters were derived retrospectively by analysis of these data.

Record	Recording Duration (minutes)	% Agreement	% Sleep (EEG)	% Sleep (Activity)
1	357	91.04	85.71	99.68
2	2838	95.81	18.68	19.84
3	1463	98.63	24.27	24.13
4	2839	98.20	20.61	21.91
5	452	90.27	97.35	92.04
6	335	95.22	97.61	97.01
7	456	80.70	88.16	75.88
8	491	90.63	91.85	87.37
9	493	90.06	90.06	82.56
10	478	91.84	96.03	95.82
11	474	85.02	82.70	96.41
12	494	83.40	81.58	92.51
13	1091	93.13	35.47	36.66
14	478	89.96	89.33	98.12
Total	12739	93.88	46.38	47.41

$r=0.9724$

Figure 10. A 48-hour activity record collected with the wearable monitor (divided into four 12-hour segments). Hours are marked along the bottom of each segment. The top trace in each segment plots the digital activity value for each minute. Below this is the EEG score (wake is solid, sleep is light) and below this the automatic activity score. The lower trace illustrates agreement between EEG and activity scoring (solid is agreement).

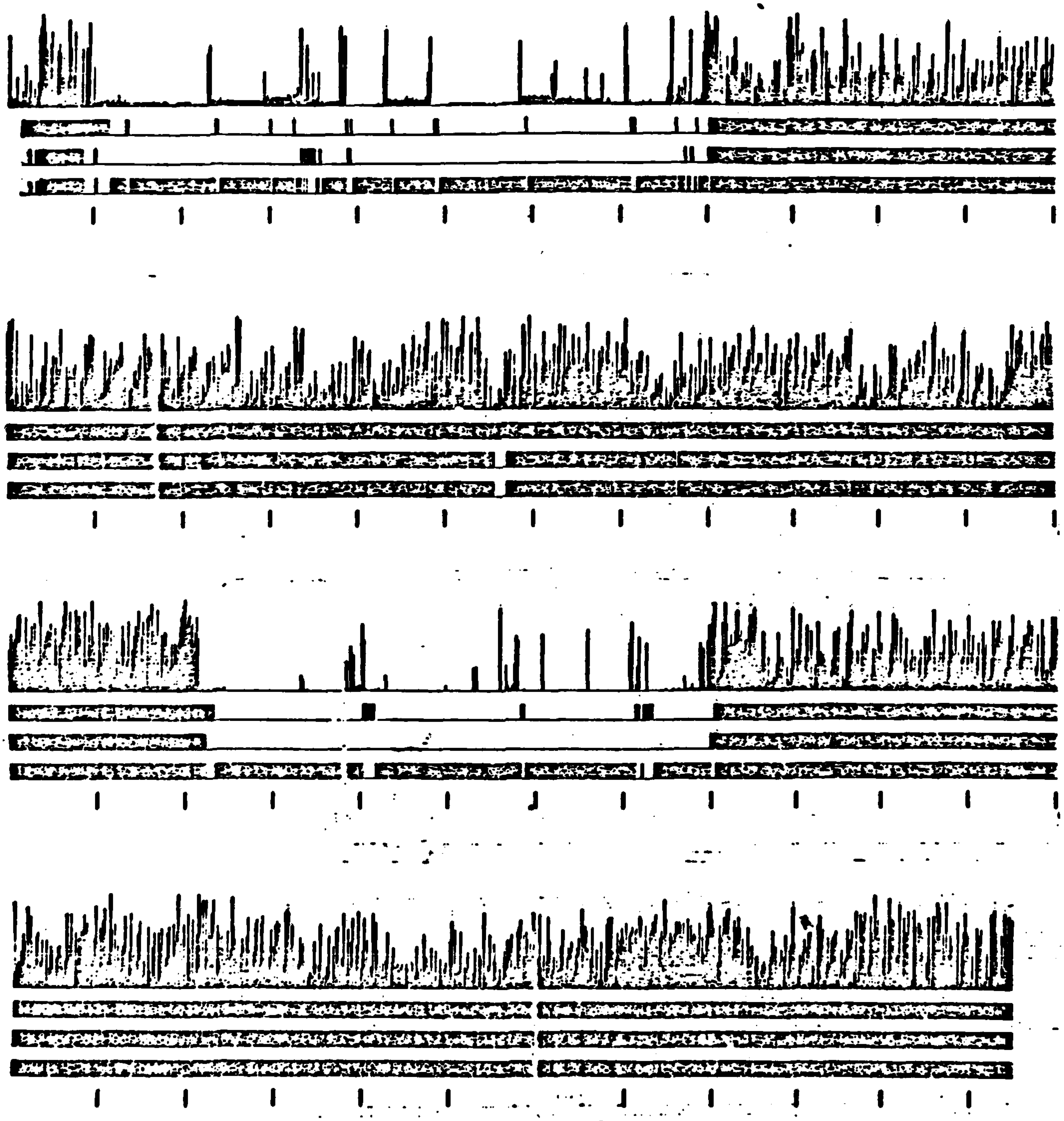


Table 4.

Record durations, proportion of the record for which EEG and automatically scored activity scores agree, proportion of the record scored as sleep by each technique, and correlation coefficient between the proportion scored sleep by the two methods. Activity data was collected with the wearable monitor. Scoring was prospective, using parameters derived from previous data.

Record	Recording Duration (minutes)	% Agreement	% Sleep (EEG)	% Sleep (Activity)
1	469	95.31	94.46	93.60
2	459	76.25	92.37	71.68
3	495	93.74	93.33	93.94
4	1302	97.00	26.57	26.80
5	2838	96.16	24.07	24.95
6	2838	97.08	25.19	26.71
7	2838	87.14	10.47	23.33
8	2593	93.21	25.92	25.38
9	2675	93.61	36.11	35.33
10	1335	93.41	34.23	29.21
11	2261	95.98	40.82	41.84
12	625	80.96	66.88	74.40
13	484	85.12	84.50	89.05
14	1302	92.93	38.56	33.95
Total	22514	93.04	34.28	35.48

$r=0.9692$

Experiment 1. The overall accuracy is more than adequate for practical utilization.

Throughout the research and development phase of this project, our goal has been to maximize the minute-by-minute agreement between EEG and activity scoring of sleep. We feel that the 90%+ agreement we have obtained in every phase of our research is very good, and it is unlikely that any alternative activity-based scoring system could reach substantially higher agreement. One reason for this is that EEG scoring is itself an estimate. Although rules have been formulated to assist in the standardization of EEG sleep scoring, scoring is nevertheless a matter of interpretation. Two raters scoring the same EEG record seldom agree 100% of the time (Mullaney et al, 1980). Some of the activity system's discrepancies with EEG estimates are certainly due to unreliability in the standard EEG scoring methods.

A second factor reducing the agreement of EEG and activity scoring in the present studies involves errors of resolution which occur in reducing the continuous processes of sleep and wake to discrete epochs. EEG recordings are usually scored in 20-30 second epochs. In our activity scoring system, the epoch was one minute. Our criterion for assigning a score of wake or sleep to a minute required that at least 50% (30 sec) be in that state. The EEG and activity methods had somewhat different responses to minutes containing brief awakenings. A final problem involved the inescapable fact that people sometimes do not move at all during times when they are awake.

Most investigators would probably assume that EEG scoring corresponds more accurately to behavioral and functional sleep than does activity scoring. While we have no objective comparisons of EEG and activity scoring as indicators of behavioral sleep, we suspect that where the EEG and activity scores were discrepant, on some occasions, behavioral criteria would favor the activity scoring. Nevertheless, reliability data indicates that the agreement between EEG and activity estimates of TST are only slightly less than agreement of two scorers rating the same EEG record. A more important issue is the well-known subject-to-subject and night-to-night variability which is observed in sleep recordings. In general, the increased quantity of data which could be gained for a given expense by automated wrist activity scoring would more than compensate in increased precision for any loss of accuracy as compared to EEG scoring.

Even if the EEG method is slightly more accurate in estimating sleep time, other factors such as simplicity and practicality make activity scoring more desirable for many purposes. The activity transducer is more comfortable and convenient for the subject, who can sleep outside the laboratory if desired, free from electrodes. The adaptability of the activity scoring method to naturalistic settings also increases its value as a measurement approach.

Although our current prototype activity scoring device is rather large and fragile for field conditions, we are certain that a device of equivalent capability could be miniaturized so that it could be worn entirely on the wrist. A wrist-mounted device could be built for military specifications of durability.

HARDWARE SPECIFICATIONS OF A WRIST-WEARABLE SLEEP MONITOR

Essentially all of the design, software, and procedural requirements have now been developed so that a miniaturized wrist-wearable sleep monitor can be built suitable for military settings. Although the actual construction, testing, and deployment of such a device is beyond the scope of this contract, we present below technical requirements for such a device. We believe a fully wrist-wearable device can be built with sufficient durability and reliability for military settings, and an appropriate read-out device can be constructed. Either current flat-pack or chip carrier technology would be adequate for miniaturization, the major problem being conservation of power and battery life.

The miniaturized sleep monitor should contain the following components or their equivalent:

1. Low-power microprocessor, processing at least 100,000 instructions per second, 8 bit word width or more.
2. Crystal-controlled hardware interrupts at 240 Hz or some multiple (1200 Hz recommended).
3. 8-K bytes of RAM memory or more.
4. A piezo-ceramic activity transducer as described in Figure 9, with appropriate buffer amplifier circuit and level shifter.
5. A single-channel A/D converter sensitive to positive and negative voltages or 2-channel positive-only A/D converter, 8-bit resolution or better and conversion rate faster than 240 Hz.
6. A facility for loading programs down into the microprocessor and restarting the microprocessor, either using a ROM controlled peripheral interface element or using direct control of the memory bus to load memory, eg, communication through DMA.
7. A facility for halting processor operations and unloading memory to an external controller, either thrugh a peripheral interface element controlled by ROM or through DMA.
8. Total system power consumption and battery supply must allow operation for at least 48 hours with facility for rapid battery change. Power consumption of less than 3 milliamps is recomended. Longer battery life is highly desirable.

The following design features are recommended but not required:

1. Program down-loading and data dump could be accomplished through optical coupling, using a self-clocking system. Two LEDs and two photocells (LED receivers) should be sufficient to implement 2-way communication. The LEDs could be controlled by I/O lines, for example, controlled through a peripheral interface element, and the software implementing this control could be housed in ROM. The photocells should have an opaque cover when not in use.
2. The unit should have a waterproof seal for all elements except the battery element should. The battery compartment should also have a waterproof gasket.
3. Parallel battery leads should be provided so that a fresh or recharged battery can be connected before a partially discharged battery is disconnected, to implement continuous operation.

4. Design of the circuit with an 8-channel multiplex analog digital converter would be useful to allow for future design expansions and implementations.
5. Inclusion of an ambient-light photocell with a window through the case, amplifier circuit, and ADC channel would be useful for sensing subject light exposure, eg, when the subject goes to bed. A sensitivity range of 1-5,000 lux or up to 50,000 lux if possible is desired.
6. If an 8-channel ADC is implemented, 3 thermistor bridges with amplifiers could be included. An external plug could allow one external thermistor to be connected. Thermistors on the top and bottom of the case could be used to detect when the instrument is taken off the wearer.
7. If the microprocessor had a low-power halt mode and could be restarted by interrupts, this capability could be used to reduce power consumption.
8. Ideally, the case should be cigarette-pack size or smaller, eg, 2x5x8 cm maximum. In our experience, a very broad leather or plastic wrist band as wide as the case is most comfortable.
9. A 4-digit LCD display controlled by the microprocessor would be extremely useful for clock and warning functions.
10. If the monitor will communicate with its external controller through DMA, the external interface must be designed. We would favor building an interface to a field-portable microprocessor such as an Apple II computer. The complete sleep scoring, readout, and display functions could be performed by a microprocessor comparable to an Apple II (16K byte 6502 processor with keyboard and display).

SOFTWARE SPECIFICATION

The logical steps necessary for sleep scoring are outlined in the preceding text and are specified exactly in the accompanying program (Appendix 1).

The software will need to be adapted for the exact configuration of wrist-wearable sleep monitor which is built, and a scaling parameter will need to be determined empirically. Operational requirements for data reporting and display will also require certain modifications of our current programs.

Now that the basic principles have been established, the hardware/software requirements for a readout device are not great. A portable microprocessor comparable to a 16K Apple II with one 5-1/4 inch disc would be sufficient for field requirements, and could easily be programmed once the report configuration desired is specified.

SUMMARY

Experiment 1 tested the idea that sleep/wake can be recognized from activity data. One hundred and two analog recordings of EEG-EOG-EMG and wrist activity were collected on cassette tape. Polygraph write-outs of the EEG-EOG-EMG channels and the activity channel were scored for sleep by

independent raters. The raters agreed 94.5% of the time, indicating that wrist activity data provides nearly the same information as electrophysiological measures for recognizing sleep.

The adequacy of the piezo-ceramic activity transducer used in Experiment 1, and its orientation and placement were investigated in Experiments 2 through 4. In Experiment 2, the transducer was compared with a tilt-switch transducer and a sensitive accelerometer and was found to be superior. Experiment 3 found the transducer to be essentially omni-directional, thus making its orientation unimportant. The suitability of the wrists for placement of the transducer was confirmed in Experiment 4.

While more efficient than EEG scoring, the analog activity recordings collected in the preceding experiments required much time for playback and interpretation by a trained scorer. A practical sleep monitor system would quantify the activity data and make it available to a computer for automatic scoring. Experiment 5 derived an algorithm for reducing two seconds of activity to a single value. The optimal algorithm also effectively eliminated any 60 Hz interference.

Experiment 6 investigated methods of interpreting the digital activity value for each two-second data epoch as sleep or wake. It was found that the largest two-second epoch score in each minute best represented activity in that minute. A given minute was scored wake if a weighted sum of this score for the given minute and for the immediately preceding and following minutes exceeded a threshold. For the 17 activity records with which these rules were dervied, automatic scoring agreed with hand EEG scoring 94.46% of the 11,002 minutes. A further three records scored prospectively with the same parameters agreed 96.02% of the time with EEG scoring.

A prototype sleep monitor system was developed. The system consists of a wrist-mounted piezo-ceramic transducer, microprocessor-controlled data compression and storage device worn on the belt, and sleep recognition software in an external computer. The unit is capable of recording wrist activity digitally for several days on a single battery charge while subjects go about their normal routine. Fourteen subjects' records were used to retrospectively derive the optimal sleep recognition algorithm for this system. Of the 12,739 minutes recorded, 93.88% were scored the same by automatic scoring and by hand EEG scoring. An additional group of 14 records were scored prospectively using the same parameters, and 93.04% of the minutes were scored the same by automatic and by hand EEG techniques. The proportion of the record scored as sleep automatically from activity and from EEG differed by 1.03% and 1.20% in the two groups, and the correlation coefficients between the two estimates of sleep across subjects were .9724 and .9692.

The electronic components of this sleep monitor system could be miniaturized with current technology into a package worn entirely on the wrist. A miniature wrist-mounted sleep monitor system would make large-scale sleep measurement feasible under field conditions.

We are extremely pleased with the success of this technical development and hope our designs can be operationally applied.

ACKNOWLEDGMENT

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APPENDIX 1

Monitor program used to control data collection, processing, and storage for wearable sleep monitor.

```
                     /ACTICORD

                     /RECORDS OUTPUT OF ACTIGRAPH TRANSDUCER AND PHOTOCELL
                     /RESOLUTION=1 MINUTE, DURATION=47HR,20MIN
                     /TIME CODE EACH MINUTE THRU L.E.D.

                     /AUTHOR: JOHN WEBSTER



                     STORE = JMS I STORE

                     /PAGE 0

                     *0

000   0000           RTNADR,   0                 /INTRPT RETURN ADDR
001   5026           INTRPT,   JMP      INTSRV   /INTRPT PNTR


                     /AUTOINDEX REGISTERS
                     *13
013   0000           A13,      0                 /RESERVED FOR A/D. . .
014   0000           A14,      0                 /BUFFER POINTER
015   0000           A15,      0                 /RESERVED FOR DIFF. . .
016   0000           A16,      0                 /SCORE POINTERS
017   0000           DATAP,    0                 /DATA STORE POINTER


                     /INTERRUPT SERVICE ROUTINE
                     *26
026   3106           INTSRV,   DCA      ACSAVE   /SAVE REGISTERS
027   7004                     RAL
030   3107                     DCA      LKSAVE
031   6504                     RCRA
032   3110                     DCA      CRASAV
033   4044                     JMS      GETACT   /GET ACTIVITY SCORE
034   1110                     TAD      CRASAV   /RESTORE REGISTERS
035   6505                     WCRA
036   6007                     CAF
037   1107                     TAD      LKSAVE
040   7010                     RAR
041   1106                     TAD      ACSAVE
042   6001                     ION               /ENABLE INTRPT
043   5400                     JMP  I   RTNADR


                     /ACTIVITY SCORE SET-UP
044   7402           GETACT,   HLT
045   1113                     TAD      AWORD    /SET UP PIE FOR A /D
046   6505                     WCRA
047   7201                     CLA IAC           /START WITH CH.1 (BIAS)
050   4066                     JMS      A2D
051   7041                     CIA
052   3121                     DCA      BIAS     /NEGATE AND SAVE
053   4066                     JMS      A2D      /THEN CH.0 (ACT)
054   1121                     TAD      BIAS     /FIND DIFFERENCE
055   3413                     DCA  I   A13      /PACK INTO BUFFER
056   1013                     TAD      A13      /RESET BUFFER PNTR. . .
057   1114                     TAD      STKEND   /IF AT END (EOB)
060   7640                     SZA CLA
```

```
061   5064              JMP      .+3
062   1111              TAD      STKBEG
063   3013              DCA      A13
064   5444              JMP  I   READAD


                /ANALOG TO DIGITAL CONVERSION
                *66
066   7402      A2D,    HLT
067   6501              WRITE1                /CHAN. SELECT
070   7300              CLA CLL
071   1115              TAD      MCNT         /SET UP BACKUP CNTR
072   3116              DCA      MCNTR
073   6511              WRITE2                /START CONVERSION
074   6513              SKIP2                 /DONE (EOC)?
075   7410              SKP
076   5073              JMP      DONE
077   2116              ISZ      MCNTR        /NO, INCR. BACKUP
100   5074              JMP      .-4
101   6500      DONE,   READ1                 /YES
102   0117              AND      X377         /MASK GARBAGE &
103   5466              JMP  I   A2D          /EXIT


                /CONSTANTS AND VARIABLES
104   0000      MAXEP,  0        /ACCUMULATES MAXIMAL EPOCH SCORE
105   0200      LITE,   0        /HOLDS LITE LEVEL VALUE
106   0000      ACSAVE, 0        /SAVES AC DURING INTRPT
107   0000      LKSAVE, 0        /SAVES LINK DURING INTRPT
110   0000      CRASAV, 0        /SAVES CRA DURING INTRPT
111   0547      STKBEG, 547      /POINTS TO ACT SCORE BUFFER
112   0000      ERROR,  0
113   0201      AWORD,  201      /INITIAL CRA VALUE
114   7221      STKEND, 7221     /-END OF ACT SCORE BUFFER
115   7766      MCNT,   7766     /TIME DELAY FOR A/D
116   0000      MCNTR,  0        /COUNTER FOR TIME DELAY
117   0377      X377,   377      /USED TO MASK A/D CONV
120   7772      M6,     -6
121   0300      BIAS,   0        /HOLDS TRANS. BIAS VALUE
122   4220      BWORD,  4220     /INITIAL CRB VALUE
123   0677      DATBEG, 677      /POINTS TO START OF RECORDER MEM.
124   0030      FLDFLG, 0        /INDICATES MEMORY FIELD (0 OR 1)
125   0000      MINCNT, 0        /MINUTE COUNT
126   0000      TCODE,  0        /TIME CODE
127   7775      M3,     -3
130   0000      GRPS,   0        /COUNTER FOR TIME CODE
131   0000      OCNTR,  0        /        "
132   7773      M5,     -5
133   0000      TCNTR,  0        /        "
134   0000      CODE1,  0        /TIME CODE '0' OR '1'
135   0000      TFLAG,  0        /TIME CODE FLAG
136   7742      M30,    -30
137   0000      MINDIV, 0        /MINUTE DIVIDER
140   0000      EPSUM,  0        /ACCUMULATES EPOCH SUM
141   0000      DFSUM,  0        /ACCUMULATES DIFSCR SUMS
142   7610      M120,   -120
143   0000      EPDIV,  0        /EPOCH DIVIDER
144   0030      SUM4,   0        /ACCUMULATES SUM TO 4
145   7774      M4,     -4
146   0000      CNT4,   0        /COUNTS 4
147   0177      X177,   177      /MASK FOR DIFSCR
150   7700      X7700,  7700
151   0300      DATWRD, 0        /HOLDS DATA PRIOR TO STORE
152   0600      CODETS, CODET    /POINTS TO TIME CODE RTN
```

```
153   0400    DFSC,     DIFSCR    /POINTS TO DIFSCR RTN
154   0000    CRATMP,   0         /TEMP CRA STORE
155   1000    FLD1,     1000      /WCRA TO GET FIELD 1
156   2001    MEMLIM,   2001      /- END OF FIELD
157   7776    M2,       -2
160   7766    M10,      -10
161   7600    T200,     7600
162   4000    O4000,    4000      /WCRA TO WAIT
163   0000    LATEST,   0         /HOLDS MOST RECENT SUM4
164   0557    BUFLOC,   557       /POINTS TO DIFSCR BUFFER
165   0000    BUFN,     0         /BUFFER LOC
166   0000    MINUS,    0
167   0000    OFLOW,    0
170   0000    PRDCT,    0
171   0640    STORE,    STORES    /POINTS TO STORE RTN
172   0000    DIFOUT,   0
173   0000    BUMP,     0
174   7765    M11,      -11
175   7770    M8,       -8
176   7777    M1,       -1
177   0077    X77,      77

              /PAGE 1

              /START-UP
              *200
200   6007    START,    CAF
201   1113              TAD       AWORD     /SET UP PIE
202   6505              WCRA
203   7300              CLA CLL
204   1122              TAD       BWORD
205   6515              WCRB
206   7300              CLA CLL
207   1123              TAD       DATBEG    /ZERO MEMORY
210   3017              DCA       DATAP
211   3151              DCA       DATWRD
212   4571              STORE
213   7410              SKP
214   5212              JMP       .-2
215   7201    WAIT,     CLA IAC             /WAIT FOR 'ON'
216   4060              JMS       A2D
217   1150              TAD       M100
220   7700              SMA CLA             /IS SWITCH ON?
221   5226              JMP       GO
222   6504              RCRA                /NO, WAIT
223   1162              TAD       O4000
224   6505              WCRA
225   5215              JMP       WAIT
226   1113    GO,       TAD       AWORD     /YES, INIT & GO
227   6505              WCRA
230   7000              NOP
231   7300              CLA CLL
232   1123              TAD       DATBEG
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233  3017            DCA     DATAP
234  3124            DCA     FLDFLG
235  3125            DCA     MINCNT
236  1111            TAD     STKBEG
237  3013            DCA     A13
240  1111            TAD     STKBEG
241  3014            DCA     A14
242  1125   MINIT,   TAD     MINCNT     /ENTER EACH MINUTE
243  3126            DCA     TCODE      /LOAD TIME CODE
244  1145            TAD     M4
245  3130            DCA     GRPS
246  1145            TAD     M4
247  3131            DCA     OCNTR
250  1176            TAD     M1
251  3133            DCA     TCNTR
252  1176            TAD     M1
253  3134            DCA     CODE1
254  2135            ISZ     TFLAG      /SET TIME CODE FLAG
255  2125            ISZ     MINCNT
256  1136            TAD     M30
257  3137            DCA     MINDIV
260  3104            DCA     MAXEP
261  3105            DCA     MINTOT
262  3140   EPOCH,   DCA     EPSUM      /ENTER EACH EPOCH
263  3141            DCA     DFSUM
264  1142            TAD     M120
265  3143            DCA     EPDIV
266  3144   FOUR,    DCA     SUM4       /ENTER EACH FOUR A/D'S
267  1145            TAD     M4
270  3146            DCA     CNT4
271  1135            TAD     TFLAG
272  7640            SZA CLA
273  4552            JMS  I  CODETS
274  6001            ION
275  7300   EACH,    CLA CLL            /ENTER EACH A/D
276  1013            TAD     A13
277  7041            CIA
300  1014            TAD     A14
301  7440            SZA                /IS A/D BUFFER EMPTY?
302  5315            JMP     NEW
303  6504            RCRA               /YES, ENTER WAIT STATE
304  7421            MQL
305  7501            MQA
306  1162            TAD     O4000
307  6505            WCRA
310  7701            ACL
311  6505            WCRA
312  7000            NOP
313  7000            NOP
314  5275            JMP     EACH
315  7300            CLA CLL            /NO, READ NEXT VALUE
316  1414            TAD  I  A14
317  1144            TAD     SUM4       /AND SUM TO 4
320  3144            DCA     SUM4
321  1014            TAD     A14        /RESET BUFFER IF AT END
322  1114            TAD     STKEND
323  7640            SZA CLA
324  5327            JMP     .+3
325  1111            TAD     STKBEG
326  3014            DCA     A14
327  2146            ISZ     CNT4       /SUMMED 4 YET?
330  5275            JMP     EACH       /NO
331  1144            TAD     SUM4       /YES, FIND DIFF. SCR.
332  4553            JMS  I  DFSCR
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333   7100        CLL
334   1141        TAD      DFSUM     /ADD TO DIFSUM
335   7430        SZL
336   7240        STA
337   3141        DCA      DFSUM     /TRUNCATE IF TOO LARGE
340   2143        ISZ      EPDIV     /IS IT AN EPOCH YET?
341   5266        JMP      FOUR      /NO
342   1141        TAD      DFSUM     /YES, FIND MAXIMAL. . .
343   7110        CLL RAR            /EPOCH EACH MINUTE
344   7041        CIA
345   1104        TAD      MAXEP
346   7700        SMA CLA            /IS THIS IT?
347   5353        JMP      .+4       /NO
350   1141        TAD      DFSUM     /YES, REPLACE OLD
351   7110        CLL RAR
352   3104        DCA      MAXEP
353   2137        ISZ      MINDIV    /IS IT A MINUTE YET?
354   5262        JMP      EPOCH     /NO
355   6002        IOF                /YES, READ LITE LEVEL
356   1363        TAD      .+5       /FROM A/D, CH.2
357   4066        JMS      A2D
360   3151        DCA      DATWRD
361   6001        ION
362   5367        JMP      .+5
363   0002        2
364   7000        NOP
365   7000        NOP
366   7000        NOP
367   4571        STORE              /AND STORE IN RECORDER
370   7402        HLT                /MEMORY
371   1104        TAD      MAXEP     /NOW GET MAXIMAL EPOCH
372   3151        DCA      DATWRD    /AND STORE IT IN NEXT
373   4571        STORE              /MEMORY LOCATION
374   7402        HLT
375   5242        JMP      MINIT
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                        /PAGE 2


                        /COMPUTE DIFFERENCE SCORE
                        *400
400   7402              DIFSCR, HLT
401   3163                      DCA     LATEST      /STORE MOST RECENT SUM
402   1164                      TAD     BUFLOC      /SET UP BUFF PNTRS
403   3016                      DCA     A16
404   1174                      TAD     M11
405   3165                      DCA     BUFN
406   3340                      DCA     MINLO       /CLEAR DP ADDER
407   3341                      DCA     MINHI
410   7300              SUM,    CLA CLL             /SUM LAST 11 SUM4'S
411   1416                      TAD  I  A16
412   7510                      SPA
413   5223                      JMP     NEG
414   1340                      TAD     MINLO
415   3340                      DCA     MINLO
416   7430                      SZL
417   7001                      IAC
420   1341                      TAD     MINHI
421   3341                      DCA     MINHI
422   5231                      JMP     NEXT
423   1340              NEG,    TAD     MINLO
424   3340                      DCA     MINLO
425   7420                      SNL
426   7240                      STA
427   1341                      TAD     MINHI
430   3341                      DCA     MINHI
431   2165              NEXT,   ISZ     BUFN
432   5210                      JMP     SUM
433   1174                      TAD     M11
434   3165                      DCA     BUFN
435   3342                      DCA     PRDLO
436   3343                      DCA     PRDHI
437   7000                      NOP
440   7300              LX10,   CLA CLL             /MUV CURR VAL
441   1365                      TAD     BUFR+5      /BY 11
442   7510                      SPA
443   5253                      JMP     LNEG
444   1342                      TAD     PRDLO
445   3342                      DCA     PRDLO
446   7430                      SZL
447   7001                      IAC
450   1343                      TAD     PRDHI
451   3343                      DCA     PRDHI
452   5261                      JMP     LNXT
453   1342              LNEG,   TAD     PRDLO
454   3342                      DCA     PRDLO
455   7420                      SNL
456   7240                      STA
457   1343                      TAD     PRDHI
460   3343                      DCA     PRDHI
461   2165              LNXT,   ISZ     BUFN
462   3240                      JMP     LX10
463   7100                      CLL
464   1340                      TAD     MINLO
465   7041                      CIA
466   3340                      DCA     MINLO
467   7430                      SZL
470   7001                      IAC
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471   1341                  TAD      MINHI
472   7041                  CIA
473   3341                  DCA      MINHI
474   7100                  CLL
475   1342                  TAD      PRDLO
476   1340                  TAD      MINLO
477   3342                  DCA      PRDLO
500   7430                  SZL
501   7001                  IAC
502   1343                  TAD      PRDHI
503   1341                  TAD      MINHI
504   3343                  DCA      PRDHI
505   1164                  TAD      BUFLOC
506   3016                  TAD      A16
507   1164                  TAD      BUFLOC
510   3015                  DCA      A15
511   1174                  TAD      M11
512   3165                  TAD      BUFN
513   1415        SHUFL,    TAD  I   A15
514   3173                  DCA      BUMP
515   1163                  TAD      LATEST
516   3416                  DCA  I   A16
517   1173                  TAD      BUMP
520   3163                  DCA      LATEST
521   2165                  ISZ      BUFN
522   5313                  JMP      SHUFL
523   1342                  TAD      PRDLO
524   7510                  SPA
525   7041                  CIA
526   7002                  BSW
527   7004                  RAL
530   0147                  AND      X177
531   5600                  JMP  I   DFSCR



                  /
                  *540
540   0000        MINLO,    0
541   0000        MINHI,    0
542   0000        PRDLO,    0
543   0000        PRDHI,    0
544   0000        SCNT,     0
545   0000                  0
546   0000                  0
547   0000                  0
550   0000        STACK,    0
551   0000                  0
552   0000                  0
553   0000                  0
554   0000                  0
555   0000                  0
556   0000                  0
557   0000                  0
560   0000        BUFR,     0
561   0000                  0
562   0000                  0
563   0000                  0
564   0000                  0
565   0000                  0
566   0000                  0
567   0000                  0
570   0000                  0
571   0000                  0
572   0000                  0
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                          /PAGE 3

                          /GENERATE TIME CODE (OCTAL MINUTES)
                          *600
600   7402                CODET,   HLT       /ENTER EACH 4 A/D'S IF TFLAG SET
601   2133                         ISZ       TCNTR     /TIME FOR ANOTHER DIGIT?
602   5225                         JMP       TOUT      /NO
603   1160                         TAD       M10
604   3133                         DCA       TCNTR
605   2131                         ISZ       OCNTR     /YES, START OCTAL GROUP?
606   5215                         JMP       FLASH     /NO, OUTPUT DIGIT
607   1145                         TAD       M4        /YES, SKIP DIGIT
610   3151                         DCA       OCNTR
611   2130                         ISZ       GRPS      /4 OCTAL GROUPS YET?
612   7410                         SKP
613   3135                         DCA       TFLAG     /YES, CLEAR TFLAG
614   5225                         JMP       TOUT
615   6506                FLASH,   STLITE              /LITE ON
616   1126                         TAD       TCODE
617   7104                         CLL RAL             /GET NEXT MSB
620   3126                         DCA       TCODE
621   7430                         SZL                 /BINARY 1 OR 0?
622   1127                         TAD       M4        /1:HOLD LITE 5 UNITS
623   1176                         TAD       M1        /0:HOLD LITE 1 UNIT
624   3134                         DCA       CODE1
625   1134                TOUT,    TAD       CODE1     /HOLD LITE ON?
626   7500                         SMA
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627  6507               CLLITE               /NO, CLEAR IT
630  7001               IAC                  /YES
631  3134               DCA      CODE1
632  5600               JMP   I  CODET


               /STORE DATA
               *640
640  7402      STORES,  HLT
641  6504               RCRA                 /SAVE CRA
642  3154               DCA      CRATMP
643  1124               TAD      FLDFLG      /WHICH FIELD?
644  7650               SNA CLA
645  5251               JMP      .+4
646  1155               TAD      FLD1        /IF FLD 1 CHANGE FLDS
647  6505               WCRA
650  7300               CLA CLL
651  1151               TAD      DATWRD      /GET DATA
652  3417               DCA   I  DATAP       /STORE IT
653  1154               TAD      CRATMP      /RESTORE CRA
654  6505               WCRA
655  7300               CLA CLL
656  1017               TAD      DATAP       /IS MEMORY FULL?
657  1156               TAD      MEMLIM
660  7650               SNA CLA
661  5264               JMP      .+3
662  2240               ISZ      STORES
663  5640               JMP   I  STORES      /NO, RETURN +1
664  1124               TAD      FLDFLG      /YES, WHICH FLD?
665  7440               SZA
666  5640               JMP   I  STORES      /FLD 1, RTRN & END
667  2124               ISZ      FLDFLG      /FLD 0, SWITCH TO FLD 1
670  7240               STA
671  3017               DCA      DATAP       /RESET DATA PNTR TO TOP
672  2240               ISZ      STORES
673  5640               JMP   I  STORES      /RTRN +1


               /RECORDER MEMORY

               /MAXIMAL EPOCH ACTIVITY SCORE AND
               /LITE LEVEL FOR EACH MINUTE ARE
               /STORED IN ALTERNATE MEMORY LOCS
               /FROM LOC. 700 TO 5777 (FLD 0)
               /AND 10000 TO 15777 (FLD 1)

               *700



               $$$
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END

FILMED

3-83

DTIC